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MILLIMETER WAVE FRONT-END FIGURE OF MERIT, PART II

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13. ABSTRACT (Maximum 200 words)

This report presents a practical approach for defining and calculating a meaningful figure of merit for frequency modulated continuous wave radar systems with separate receive and transmit (bistatic) antennas.

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CONTENTS

INTRODUCTION

This report presents a practical approach for defining and calculating a meaningful figure of merit (FOM) for the frequency modulated continuous wave (FMCW) radar system with separate receive and transmit antennas. The purpose for generating this FOM calculator was to estimate the systems's noise floor and dominant noise sources prior to design assembly; hence, enabling the designer to address the dominant noise sources early in their design. In the past, the contractor involved with the U.S. Army Armament Research, Development and Engineering Center's (ARDEC's) precision munitions programs measured and addressed the noise floor after the front-end assembly, which usually resulted in a long and costly project.

The FOM for FMCW systems is presented in two reports. The first report, published March 1994, presented general definitions, descriptions, and equations for the FOM, mainly addressing FOM theory. This is the second report which presents the practical detail on this topic. A FOM calculator code written in MATLAB, which is provided in the appendix, will be discussed with a brief explanation of input variables and associated calculations.

INPUT VARIABLES

There are 31 input variables that this FOM calculator requires. Most of these input variables are self-explanatory and will not be discussed in this section. The user can either enter input variables interactively or load them from a previously stored file. The fom.def file is the default file where previously defined values are stored; however, the user also has an option to read or write data from or to any user specified file. Figure 1 presents the block diagram of a typical FMCW front-end where origination of each input variable is shown.

The oscillator noise is a combination of amplitude and phase noises. There are equations available to estimate these noise sources; however, it is best to actually measure them to arrive at more accurate values. Measuring oscillator noise is not a trivial task; there are numerous articles on this subject. Several good techniques are described in references 1 and 2. Be sure to pay particular attention to the dynamic range of the measuring instrumentation since this is the most common deficiency made during phase noise measurement. The two oscillator noise components prompted by the FOM calculator are: **ampsd,** the oscillator's amplitude mod-ulation (AM) noise in decibels below the carrier per 1 Hz bandwidth [dBc/Hz]; and **fd**, the oscillator's phase noise equivalent root mean square (RMS) frequency deviation within a specified bandwidth. The input **fd** is defined in reference 1, chapter 1 and the author calls it Residual Frequency Modulation (FM), equation 1.22.

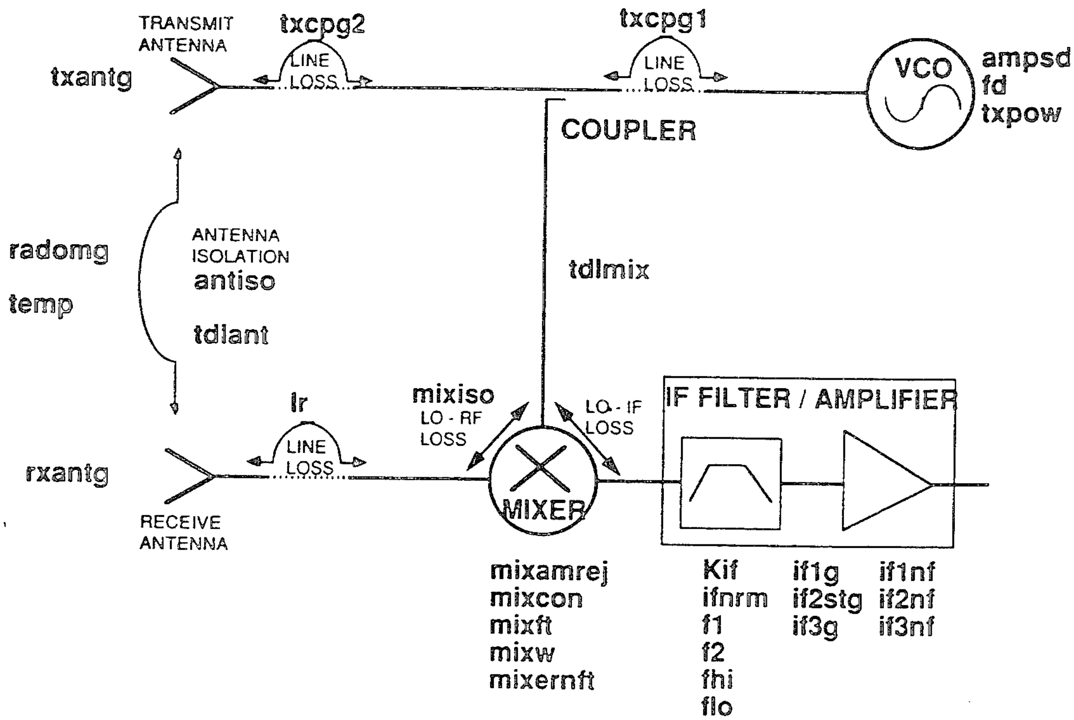

Figure 1
FMCW transceiver figure of merit model with depicted input variables

This calculator assumes a three stage intermediate frequency (IF) amplifier with the second stage being an IF filter. Hence, the calculator prompts for three noise figure and gain values associated with the IF amplifier/filter stage. The **ifnrm** is the filter's normalization factor accounting for the filter passband not being normalized at the peak. The input variable **Kif** is the IF transfer function equalization, which is a function of circuit implementation. **lr** is the transmission line loss between the receive antenna and the radio frequency (RF) to IF mixer. The next six variables are: mixer AM rejection **(mixamrej)**; mixer conversion gain **(mixcon),** which is actually a loss and should be a negative number; mixer RF to local oscillator (LO) isolation (**mixiso**); frequency at which mixer noise figure (NF) was measured (**mixft**); single side band (SSB) noise figure at the test frequency (**mixnft**); and mixer weighting factor (**mixw**). The **mixw** is the only mixer input variable that is not self-evident. Variable **mixw** is a parabolic weighting factor which was derived from measured data. Users of this calculator are cautioned that this weighting factor approach does not account for mixer leakage sources. The one-way signal gain through radome, which is actually a loss, is represented by **radomg** and has to be inputed as a negative number. Receive antenna gain is represented by **rxantg**. This value incorporates the mismatch between the receive antenna and the receiver. The following two variables, **tdlant** and **tdlmix**, are the time delays through the antenna and mixer leakage paths, respectively. Parameters are fed into calculating the phase noise contributlon by leakage paths. The **tdlant** consists of two parts: the reflection from the radome path and the surface waves (when transmit and receive antennas are located on the same dielectric material). There are two possible mixer leakage paths as well, the LO to IF path, and the LO to RF to IF path. The LO to IF path can be neglected because the frequency content is usually outside the IF filter passband; therefore, **tdlmix** is the time it takes the transmitting signal to propagate through the LO to RF to IF leakage path. The **txantg** is the transmit antenna gain value which consists of the antenna gain and the mismatch loss between the transmitter and the antenna. The **fhi** and **flo** are high and low frequency edges of the IF passband. The **f1** and **f2** are transfer function poles.

CALCULATIONS

The calculations are performed partially in the decibel (dB) realm and partially in linear form. The IF filter transfer function, **trans,** is an application specific function which the user has to custom define for a desired application. The filter in the calculator was designed as a bandpass filter with 12 dB per octave low frequency edge roll-off. The IF filter is incorporated into the model as part of the variable **if2g**. However, the filter should not be treated as a lump in one spot; it is actually spread throughout the three stages. Therefore, to more accurately account for its effect, the filter's transfer function is assumed to be in the middle with attenuation factor **(ifnrm/Kif)** to account for the reduced gain in the first stage. The parameter **ifg** is the total IF gain weighted by the IF filter. The **alnpw** and **mlnpw** are the AM noise power in watts/hertz due to

the antenna leakage path and the mixer leakage path, respectively. The **fn** is the SSB noise factor, which includes the mixer and the IF amplifier, calculated by Friis' equation as shown in part 1 of this report. It is assumed that circuit components prior to the mixer on the receive channel are at the thermal noise floor and are incorporated in variable **ts**. The most dominant noise factor contributor, **fnmixt**, mixer noise factor is weighted by **mixw** for better representation of the actual hardware. **ts** is the effective thermal noise temperature, as described in part I of this report. Thermal noise, **ntherm**, is referenced at the receiver output and it is in units watts/hertz. The **pnlkant** is the antenna path phase noise power contribution excluding the contribution due to mixing. The antenna path phase noise density function is calculated in **pnantden**. The phase noise density function equation is derived in detail in reference 1. Similar phase noise calculations are performed for the mixer LO to RF to IF path where **pnlkmix** is the mixer phase noise contribution excluding the mixing effect and **pnmixden** is the mixer path phase noise density function. Both density functions are summed in **pnden**. The receive channel gain, **grec**, and effective radiating power, **erp**, are self-evident. Both values are calculated in decibels and include line loss, radome attenuation, antenna gains, and front-end gain. The **ifnpdbm** integrates all the noise contributions over IF bandwidth. This is the total noise thats allowed to pass further into the signal processing section of the system. **fom**, as defined in part I, is then finally calculated.

CONCLUSIONS

The figure of merit (FOM) calculator for an frequency modulated continuous wave (FMCW) system was presented with a fair explanation of the calculator's entry variables and associated calculations. This calculator successfuly predicted the performance of actual hardware within 1 dB. There is one weakness of this calculator, the need for a parabolic weighting factor, **mixw**, which is an approximation determined from the measured data. It is evident that the FOM calculator is missing a thorough model of all possible mixer leakage sources. There are further plans to investigate whether the transmit signal triple travel (i.e., the reflected transmit wave from the local oscillator (LO) coupler to the mixer, back to the coupler, back to the mixer) on the LO line leaking through the radio frequency to intermediate frequency path is a significant contributor to the noise. If triple travel is found to be a significant noise contributor, then triple travel leakage will be incorporated into the FOM calculator model and incorporation of five bounces on the LO line will be considered.

This FOM calculator proved to be extremely useful in predicting FMCW radar front-end hardware performance during individual component testing stages. Furthermore, this calculator helped in determining dominant error sources early in the circuit layout design phase.

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APPENDIX
FOM CALCULATOR CODE WRITTEN IN MATLAB

```
%
% This matlab program calculates FOM for an FMCW radar transceiver.
%
whl=1;
while whl==1,
chs=menu('choose an input','read data from fom.def file',...
'input data interactively','read data from not fom.def file');
kb=1.3807e-14;
if chs==2,
   ampsd=input('enter OSC. AM noise relative to fc [dBc/Hz]:  ');
   antiso=input('enter isolation between transmit and receive antennas
[dB]:  ');
   fd=input('enter phase noise equivalent FM deviation [MHz]:  ');
   if1nf=input('enter the IF 1st stage noise figure [dB]:  ');
   if2nf=input('enter the IF 2nd stage noise figure [dB]:  ');
   if3nf=input('enter the IF 3rd stage noise figure [dB]:  ');
   if1g=input('enter the gain of the 1st IF stage [dB]:  ');
   if2stg=input('enter the gain of the 2nd IF stage [dB]: ');
   if3g=input('enter the gain of the 3rd IF stage [dB]:  ');
```

```
ifnrm=input('enter the normalization factor of the IF filter: ');

Kif=input('enter IF transfer function equalization:  ');

lr=input('enter loss between the receive antenna and the mixer
[dB]:  ');

mixamrej=input('enter mixer AM rejection [dB]: ');

mixcon=input('enter mixer conversion gain [dB]:  ');

mixiso=input('enter RF-LO isolation [dB]:  ');

mixft=input('enter freq of mixer NF test - weighted by (1/f)^mixer
weight factor [Mhz]:  ');

mixernft=input('enter SSB mixer noise figure at test freq. mixer
[dB]: ');

mixw=input('enter mixer 1/f weighting factor [unitless]:  ');

radomg=input('enter radome gain [dB]:  '); rxantg=input('enter
receive antenna gain [dB]:  ');

tdlant=input('enter time delay of antenna leakage path [usec]:  ');

tdlmix=input('enter time delay of mixer leakage path [usec]:  ');

temp=input('enter ground temperature [K]:  ');

txantg=input('enter transmit antenna gain [dB]:  ');

txcpg1=input('enter loss from OSC to LO tap [dB]:  ');

txcpg2=input('enter loss from LO tap to antenna feed [dB]:  ');
```

```
txpow=input('enter transmitter output power [dBm]:  ');

elseif chs==1, load fom.def;

else,

fnn=input('enter file name','s');

load fnn;

end

fhi=input('enter upper limit frequency of the bandwidth: ');

flo=input('enter lower limit frequency of the bandwidth: ' );

f1=input('enter first transfer function pole:  ');

f2=input('enter second transfer function pole:  ');

%

% the data entry part is complete

%

% Now lets define our filter transfer function

%

%***** WARNING ********: EVERY USER SHOULD MODIFY THIS TRANSFER

%*********************** FUNCTION TO REFLECT THEIR OWN IF

%*********************** TRANSFER FUNCTION

%

fdel=(fhi-flo)/1000;
```

```
f=flo:fdel:fhi;

t=(ifnrm/Kif).*((f.^4)./((f.^2-f1^2).^2+(f*f1/1.25).^2));

r=((f2^4)./((f.^2-f2^2).^2+(f*f2/1.25).^2));

trans=t.*r;

if2g=if2stg+10*log10(trans);

ifg=if1g+if2g+if3g;

ten=10*ones(if2g);

alnpw=ten.^(0.1*(ampsd+txpow-txcpg1-txcpg2+antiso-lr+mixcon+ifg));

mlnpw=ten.^(0.1*(ampsd+txpow-txcpg1+mixiso+mixcon+mixamrej+ifg));

fnmixt=10^(0.1*mixnft);


fn=2*(fnmixt*(mixft./f).^mixw+((10^(0.1*if1nf)-1)/(10^(0.1*mixcon)))..

.


+((10^(0.1*if2nf)-1)/(10^(0.1*(mixcon+if1g))))+((10^(0.1*if3nf)-1)./...

((10).^(0.1*(mixcon+if1g+if2g)))));

%

ts=temp*fn*(10^(0.1*lr));

ntherm=kb.*ts.*(10).^(0.1*(mixcon+ifg));

pnlkant=(10).^(0.1*(txpow-txcpg1-txcpg2+antiso-lr+mixcon+ifg));
```

```
pnantden=(((fd)./f).^2)*2*[pnlkant]'*(1-cos(2*pi*f.*tdlant));

pnlkmix=(10).^(0.1*(txpow-txcpg1+mixiso+mixcon+ifg));

pnmixden=(((fd)./f).^2)*2*[pnlkmix]'*(1-cos(2*pi*f.*tdlmix));

pnden=pnantden+pnmixden;

grec=rxantg+radomg-lr+mixcon+if1g+if2stg+if3g-10*log10(Kif);

erp=txpow-txcpg1-txcpg2+txantg+radomg;

ifnpdbm=10*log10(max(cumsum(pnden+ntherm+alnpw+mlnpw)));

fom=erp+grec-ifnpdbm+10*log10(max(cumsum(kb*temp*Kif*trans)))

op=menu('Select where to save the entry data','fom.def file',...

'user specified file','Quit without saving')

if op==1,

save fom.def ampsd antiso fd if 1fn if2fn if3fn if1g if2g ...

if3g ifnrm Kif lr mixamrej mixcon mixiso mixft mixernft mixw ...

radomg rxantg tdlant tdlmix temp txantg txcpg1 txcpg2 ...

txpow

elseif op==2,

svfn=input('Enter file name','s');

save 'svfn' ampsd antiso fd if1fn if2fn if3fn if1g if2g ...

if3g ifnrm Kif lr mixamrej mixcon mixiso mixft mixernft mixw ...

radomg rxantg tdlant tdlmix temp txantg txcpg1 txcpg2 ...
```

```
txpow
end
whl=menu('What shell I do next','Run the program again','Quit')
end,
```

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